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HIGH INTENSITY NEUTRINO SOURCE SUPERCONDUCTING SOLENOID CRYOSTAT DESIGN

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ABSTRACT

Fermi National Accelerator Laboratory (FNAL) is involved in the development of a 100 MeV superconducting linac. This linac is part of the High Intensity Neutrino Source (HINS) R&D Program. The initial beam acceleration in the front end section of the linac is achieved using room temperature spoke cavities, each of which is combined with a superconducting focusing solenoid. These solenoid magnets are cooled with liquid helium at 4.5K, operate at 250 A and have a maximum magnetic field strength of 7.5 T. The solenoid cryostat will house the helium vessel, suspension system, thermal shield, multilayer insulation, power leads, instrumentation, a vacuum vessel and cryogenic distribution lines. This paper discusses the requirements and detailed design of these superconducting solenoid cryostats.

KEYWORDS: Cryostat, solenoid, power leads, HTS leads, vacuum vessel.

INTRODUCTION

The High Intensity Neutrino Source (HINS) is an R&D Program at Fermilab to design and build the front end of a high power H- RF linac [1]. Initial acceleration of the beam is achieved by a Radio Frequency Quadrupole (RFQ) from 0.05 MeV to 2.5 MeV and room temperature (RT) accelerating cavities up to ~10 MeV in what is called the RT section of the linac [2,3]. Each of these cavities is combined with a superconducting solenoid to provide beam focusing. The use of superconducting solenoids in this region permits shorter focusing periods and a more compact lattice. FIGURE 1 shows a layout of the RT section.

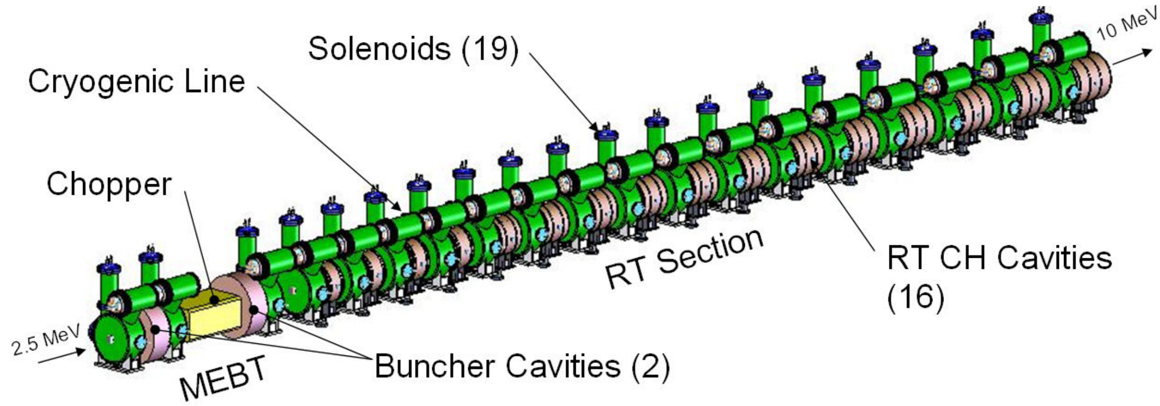

FIGURE 1. RT Section layout showing the solenoid and cavity focusing pairs.

There are 19 cryostated solenoid magnets installed in the front end. Three of these are in the Medium Energy Beam Transport (MEBT) section of the linac while the remaining 16 are in the RT section of the linac. Out of these 19 solenoid magnets, 8 will have horizontal and vertical dipole correction coils installed on the inner diameter of the solenoid coil. The solenoid without the correction coils is designated as Type-1 and the solenoid with correction coils is designated as Type-2. The addition of the dipole correction coils also adds two pairs of power leads to the cryostat. Since the power leads are housed inside the cryostat, a separate cryostat design for each type of solenoid magnet is required.

Seven solenoid magnet coils have been fabricated and tested to date [4,5]. Two of these magnets had the dipole correction coils installed. These were all tested in a vertical cryostat at the Fermilab Magnet Test Facility. The solenoid magnet design and operating parameters are shown in TABLE 1.

CRYOSTAT DESIGN

The cryostat design for these solenoid magnets is challenging due to tight axial space requirements and the fact that there is a warm RF cavity between each cold solenoid. This requires that the beam tube through the solenoid be at room temperature. In a typical superconducting magnet installation, all of the cold elements are connected in long uninterrupted strings. Interconnects are installed between magnets to connect the beam tube, cryogenic circuits and the insulating vacuum space. It is only at the ends of the string where the insulating vacuum space is capped off. In this design, each magnet is installed in a standalone cryostat so there are end walls on each vacuum vessel and a warm bore through the center. The cryogens get transferred from cryostat to cryostat through a cryogenic distribution line.

TABLE 1. Design and operating parameters of the solenoid magnets.

Parameter	*Value*	*Units*
Operating temperature	4.5	K
Operating current	250	A
Magnetic field strength	7.5	T
Coil length / diameter	130 / 174	mm
Helium vessel length / diameter	150 / 203.2	mm
Vacuum vessel length / diameter	270 / 457.2	mm

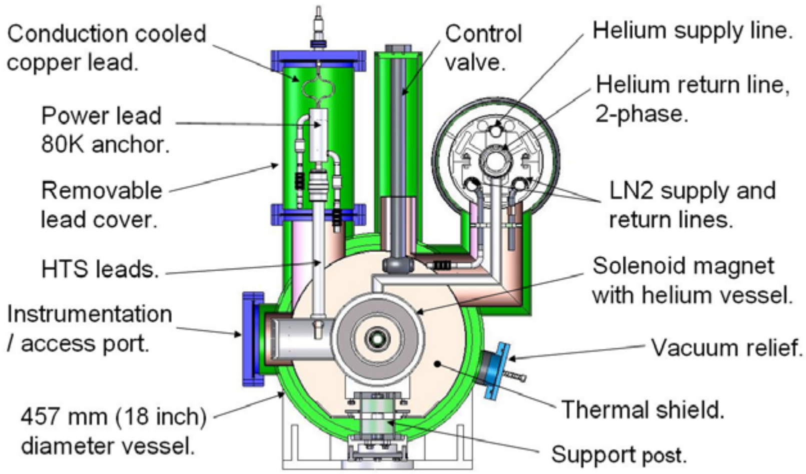

FIGURE 2. Cross-section through the Type-1 solenoid cryostat.

Also challenging in this design is the fact that the power leads are not housed in the cryogenic feed box but rather in the individual solenoid cryostats. The Type-1 solenoid cryostat will have one pair of power leads while the Type-2 solenoid cryostat will have three pairs so that the correction coils can be independently powered.

Other than the unique features described above, these cryostats are similar to other superconducting magnet cryostats. There is a helium vessel, a thermal shield, MLI around each cryogenic system, a cold mass support structure, a vacuum vessel and instrumentation wires that make their way from inside the cryogenic systems to outside the vacuum vessel. The first prototype cryostat assembly has been started as of this writing and is expected to be complete by fall of 2007. FIGURE 2 shows a cross section through the Type-1 cryostat.

Helium Vessel

The cooling for these solenoid magnets is achieved by 4.5K pool boiling helium. Single phase helium is fed from the upstream end of the system to the downstream end, through a JT valve and 2-phase helium flows back through a 73 mm (2 inch IPS) diameter return line. There is a pipe which tees off from the return line into the top of the helium vessel which fills the vessel as well as allows boil-off gas to flow back to the return line. The liquid level of the system is set inside an upstream feed box to ensure the solenoids are always submerged in liquid helium. FIGURE 3 shows a model of the helium vessel along side a picture of the prototype solenoid mounted inside the vessel.

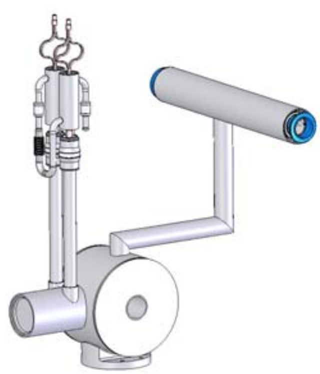
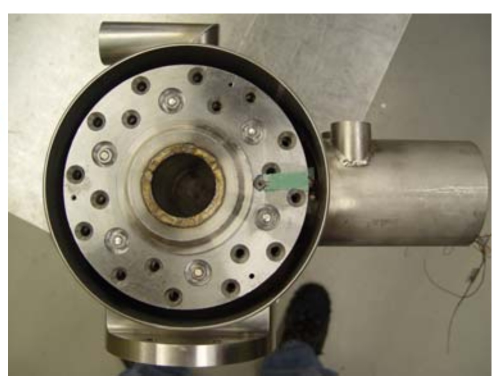

FIGURE 3. The solenoid helium vessel. (Left) A model of the helium vessel shown with its piping attached. (Right) A picture of the prototype solenoid mounted inside the helium vessel.

There is a port on one side of the helium vessel which serves as a structural support for the power leads and provides space for the splice between the coil and lead wires. This will also serve as an access port into the helium vessel should there be a need to repair or replace a power lead. Another feature built into the helium vessel is an integral support post mounting bracket. This allows for precise alignment of the magnet coils during assembly into the vacuum vessel.

LN_2 System

There is liquid nitrogen available at the installation point so it was decided to use nitrogen to cool the top end of the power leads as well as the thermal shield. There will be a control valve in each cryostat to control the nitrogen to the power leads. The LN_2 flow to the cryostats will be parallel which ensures each set of power leads gets cold nitrogen. This is critical to the performance of the power leads. The top end needs to be below 82 K. Once through the top end of the power leads, the nitrogen will flow through piping attached to the thermal shield and up to the nitrogen return line. The expected operating temperature of the thermal shield is between 80 and 90 K.

Cryogenic Distribution Line

The cryogenic distribution line provides for transfer of cryogens from an upstream feedbox to all 19 solenoid cryostats. This distribution line will house the helium single phase supply line, the helium 2-phase return line and the nitrogen supply and return lines. There will be an interconnect at both ends of each cryostat in which to make the mechanical connections between the cryogenic lines. Each line will have bellows attached directly to the pipes which allow for up to 10 mm of adjustment in either direction. Metal seals with split clamping collars, similar to those installed in Fermilab's Tevatron, will be used instead of welded connections. This type of connection has proved reliable over many years of use in the Tevatron and makes installation and removal of the cryostats straightforward with no cutting or grinding required.

Since there are warm cavities between each solenoid, the distribution line is offset from the beam axis of the system. This requires all of the internal cryogenic piping to be routed through a 90° elbow and into the distribution line. Assembly of this line is achieved through a muli-step process starting from the inside and working outward to the vacuum shell. The elbow sub-assembly is completely assembled and leak checked prior to welding to the vacuum vessel. FIGURE 4 shows various steps in the assembly process of the distribution line elbow sub-assembly.

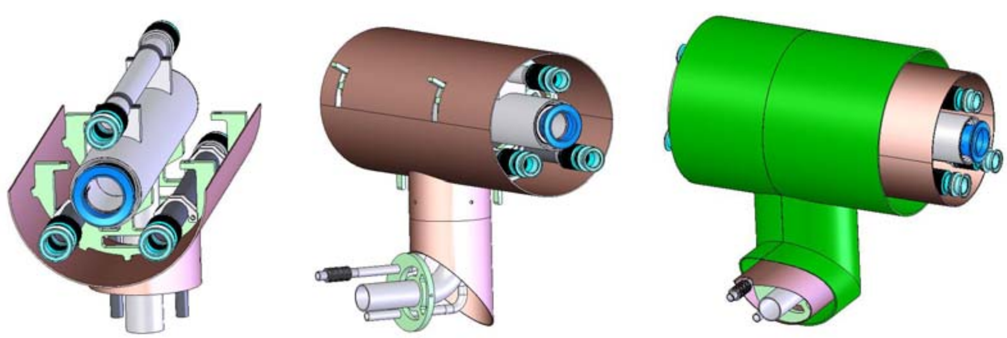

FIGURE 4. Various steps in the cryogenic line distribution assembly process.

Support Post

The suspension system chosen for this cryostat was a support post. Support posts have been used in a number of superconducting magnet designs including SSC, RHIC and LHC. Construction of this type of support post consists of shrink fitting metal rings onto a G11 composite tube. The size and tolerance of the rings is critical to the performance of the shrink fit joint. This post was designed using a similar method as described in [6]. The ring materials chosen for this post are stainless steel for the top and bottom rings and aluminum for the center ring. The center ring attaches to the thermal shield which provides mechanical support for the shield as well as an 80 K intercept on the G11 tube. The top ring attaches to the helium vessel at 4.5 K while the bottom ring attaches to the vacuum vessel at 300 K. FIGURE 5 shows a cross section through the support post.

A single post was chosen for this cryostat due to the tight space requirements and the small size of the cold mass. When using a single post, one has to worry about the rotation of the cold mass after installation and alignment inside the vacuum vessel. Two set screws are used to lock the position of the solenoid cold mass with respect to the post after the alignment is set. This in turn locks the position of the solenoid with respect to the vacuum vessel since the post is bolted directly to the vacuum vessel. A prototype post has been built and failure tests of post assemblies are planned in the near future.

Multilayer Insulation

The insulation system in this cryostat is typical to the multi-layer insulation (MLI) used in other superconducting magnets. It consists of alternating layers of reflective Mylar and nylon spacer. Since spacing is tight, special care will need to be taken when installing the MLI as not to create thermal shorts to the vacuum vessel. This is especially true in the region of the warm beam tube. There is approximately 4 mm of radial space in which to install the MLI. This small gap does not leave much room for the MLI but it is anticipated to install between 3 and 5 layers in this area. With this amount of insulation, the expected heat load is between 0.5 W and 1 W to 4.5 K. The cold mass and thermal shield will have 10 and 20 layers, respectively.

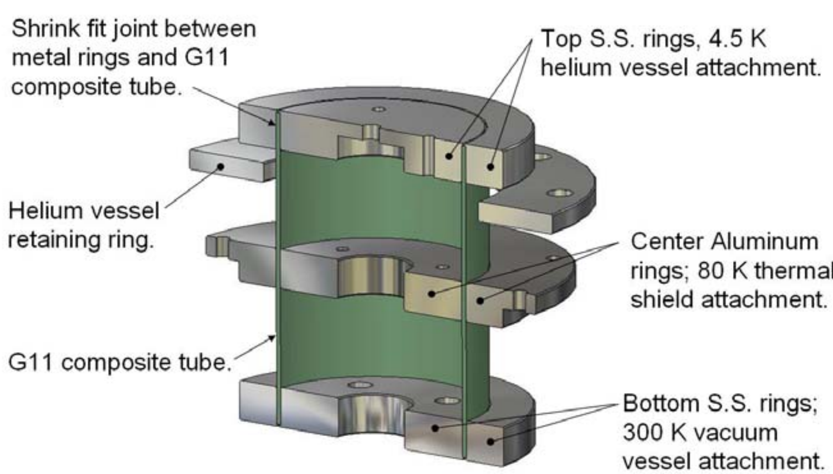

FIGURE 5. Cross section of support post. MLI is installed on the interior surfaces of the post but is not shown in this figure.

Power Leads

These cryostats will be installed in the Meson Detector Building at Fermilab. This building has an existing helium refrigerator and nitrogen supply which is shared with other experiments and installations in the same facility. Due to this sharing, the amount of helium available for operations is limited. Early in the conceptual phase, it was decided to use HTS leads to reduce the heat load to the helium system. These will be used for the Type-1 cryostats only. The Type-2 cryostats will use standard vapor cooled leads since three pairs of the HTS leads will not fit into the allowed space. This is due to the correction coils being added to the solenoid design after both the Type-1 cryostat and HTS lead designs were complete. The original designs were complete on the basis of one pair of HTS leads, not three pairs as is the case in the Type-2 cryostat.

It was decided early on in the project that Fermilab would design the upper conduction cooled part of the lead and industry would make the lower HTS section of the lead. The upper section consists of a conduction cooled flexible copper strand connected to a ceramic feed through at the room temperature end and an 80 K heat exchanger at the top of the HTS lead. Liquid nitrogen provides cooling for the 80 K heat exchanger. There are ceramic breaks on the nitrogen tubes going into and out of the heat exchanger to isolate the tubes from the live current. Details of the heat exchanger and conduction cooled strand design are outside the scope of this paper. FIGURE 6 shows a schematic of the complete lead. A prototype of the complete upper section has be fabricated and tested and performs as expected.

Two pairs of prototype HTS leads have been ordered and received and are being prepared for testing. Once successfully tested, the production quantity will be ordered. Since the testing will not be complete in time for installation into the prototype cryostat, standard vapor cooled leads will be used in this assembly.

Vacuum Vessel

The vacuum vessel for these solenoids is complicated due to the number of components which must fit in a relatively small space. One of the main features included in the Type-1 vacuum vessel design is access to the power leads without having to cut into the vessel. This was deemed necessary due to the five cold ceramic insulators per cryostat that are required for the HTS leads. It is highly probable that one of these ceramics will fail during the operating life of these cryostats. Therefore, a removable extension tube was designed in which all of the power lead ceramic insulators were located. Once removed, the insulators can be accessed and replaced. FIGURE 7 shows the concept of the removable extension tube.

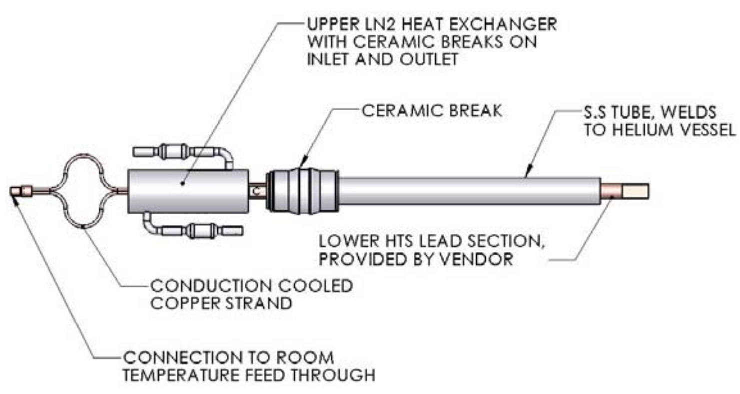

FIGURE 6. Schematic of HTS lead.

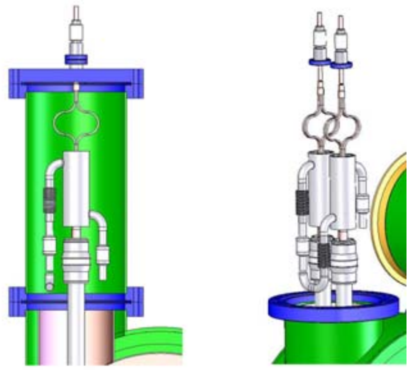

FIGURE 7. Removable lead extension tube concept. (Left) A cross section through the extension tube showing the position of the power leads. (Right) Ceramic insulators accessible after removal of tube.

The Type-1 and Type-2 vacuum vessels are identical except for the lead extension tube. The Type-2 solenoid will have three pairs of vapor cooled leads so the removable extension tube is not necessary. There will be a transition tube which will mount to the same flange of the vacuum vessel side of the tube but will be welded to an adapter at the top end of the lead. FIGURE 8 shows a completed Type-1 cryostat assembly.

SUMMARY

The design of the cryostat is nearly complete. As of this writing, there is a vacuum vessel, a solenoid coil, a helium vessel, a pair of vapor cooled leads and the cryogenic distribution line piping sub-assemblies in stock ready for assembly into the first prototype. The thermal shield, internal piping and remaining vacuum component drawings have been reviewed and will soon be released for procurement. Final assembly and testing of the prototype is expected to be complete this calendar year. Procurement and fabrication of the production cryostats will take place over the next year and a half.

Testing of the completed cryostat assemblies will take place at the Fermilab Magnet Test Facility. An adapter is needed to interface these cryostats with one of the existing test stands. Design of this adapter along with the cryogenic feed and return boxes are scheduled to begin in the near future.

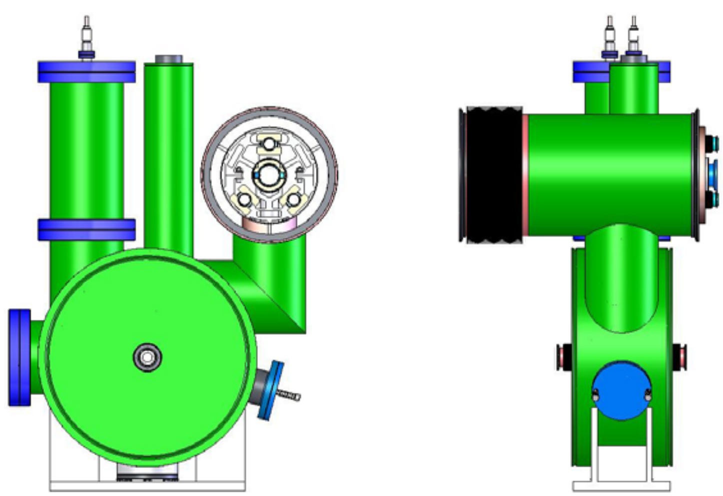

FIGURE 8. Complete Type-1 cryostat assembly. (Left) Front view. (Right) Side view.

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